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# Analysis of Near-Field Hydrodynamics of Submerged Weirs

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**PURPOSE:** This Coastal and Hydraulics Engineering Technical Note presents the results of three-dimensional numerical model simulations of Victoria Bendway in the Mississippi River. The primary purpose of this study was threefold: (a) to better understand the near field hydrodynamics adjacent to submerged bendway weirs, (b) to provide insight into the effectiveness of submerged weirs for improving navigation in bendways, and (c) to determine optimum design variables and flow conditions for improving weir field design.

**BACKGROUND:** Over the last decade, the U.S. Army Corps of Engineers has been constructing submerged weirs in river bends to improve navigation conditions and consequently reduce dredging. The most effective prototype submerged weir fields were initially evaluated in small-scale physical models (Waterway Simulation Technology, Inc., 1999).[1] However, some weir fields are currently designed and constructed based on the success of previous installations and very little design guidance. A summary of bendway weir construction practices was prepared as an initial design guide for submerged weir installations (LaGrone 1995).[2] It provides a qualitative approach to bendway weir design based on information gleaned from experts involved in previous weir field installations.

The primary function of submerged weirs is to realign the flow by reducing or disrupting the bendway secondary helical flows. In bendways without weirs, the transverse helical flow resulting from centrifugal forces redirects the surface flow against the outer bank. Tow navigation entering the bendway tends to follow the flow lines and is therefore forced toward the outside bank. The tow must then execute maneuvers to realign within the channel thalweg, risking collision with the outer bank or running aground on the shallow point bar adjacent to the inside of the bend. Another benefit of the reduction in magnitude of the helical flow is bank protection between the weirs (provided that there are a sufficient number of weirs to prevent the secondary flow from reforming in the bendway). Additionally, scour occurs at the tip of the weirs and behind the weirs. This generally results in a widening and deepening of the bendway. In summary, the primary beneficial effects of the weirs are flow realignment, bank protection in the bendway, and a deeper, wider navigation channel.

Small-scale physical model testing and observations of prototype bendway weir installations indicate that flow across a submerged weir angled upstream tends to become perpendicular to the downstream face of the weir, thus realigning the flow back towards the center line (thalweg) of

[1] Waterway Simulation Technology, Inc. (1999). "A physical model test plan for bendway weir design criteria," Project report to U.S. Army Engineer Waterways Experiment Station.
[2] Lagrone, David. (1995). "Reverse sill (bendway weirs) general guidance," unpublished letter report, U.S. Army Engineer Waterways Experiment Station.

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the channel. The general rule of thumb is that the severity of the weir angle is determined by the position of the weir in the bend, i.e., entrance and exit weirs have slight angles whereas weirs in the apex of the bend are angled the most. The design goal is to have enough weirs in the bend at the proper angle to maintain the highest flow distribution in the channel thalweg.

The research effort reported in this Technical Note investigates the impact of the Victoria Bend weir field on bendway hydrodynamics. A three-dimensional model was used to evaluate the flow field in Victoria Bend with and without the weir field. Emphasis was placed on analyzing the three-dimensional secondary flow field adjacent to the weirs, and the affect of the weirs on bendway flow distribution. The three-dimensional model was verified to a comprehensive set of field data collected in June of 1998.

**INTRODUCTION:** Victoria Bend in the Mississippi River is located approximately 958 km above Head-of-Passes (AHP) in the Gulf of Mexico, bordered by Arkansas on the west and Mississippi on the east. It is located just below the confluence of the White River with the Mississippi River. A cutoff of the White River connects the Mississippi River channel above and below the bend (Figure 1). Six submerged weirs were placed on the outside of the bend to improve navigation. Additionally, three dikes were placed on the inside of the bendway to maintain a deep channel. The weirs were spaced approximately 152 m apart, with angles oriented with the upstream direction at 69 to 76 deg from the horizontal. The bend has a heading change of 108 deg with a radius of 1,280 m. Preconstruction surveys indicate bottom elevations ranging from el 13 to 18,[1] with weir heights ranging from el 7 to 13. The average water depth over the weirs is approximately 11 m, with an approximate range of 7 to 19 m. The weirs were sited 6 m below the 1993 low-water reference plane (approximately 27 m NGVD) to insure that the weirs do not interfere with navigation at low water. Postconstruction surveys indicate deposition at the first weir, with significant scour below each weir, particularly the lowermost in the reach. Bed elevations in the scour holes were as low as el 3.

Pilot ratings/comments for Victoria Bend show a degradation of navigation conditions post-construction (Waterway Simulation Technology, Inc., 1999). Tow pilots indicated that excessive turbulence was encountered for both northbound and southbound tows. They indicated that the weirs resulted in higher flows on the lower end of the bend, with crosscurrents forming when flows over the weirs encounter flows returning from the inside of the bend. The survey data and model data confirm the higher flows in the downstream leg of the bend and the conflicting main channel flows. A deep, relatively long scour hole exists below the last downstream weir (Figure 2).

**MODEL AND PROTOTYPE FIELD DATA DESCRIPTION:** The three-dimensional numerical model used to conduct the study was developed at the Center for Computational Hydroscience and Engineering at the University of Mississippi (CCHE3D) with funding provided by the Agricultural Research Service. It is a finite element-based hydrodynamic and sediment transport model that solves unsteady, free-surface flows. Additional information about

[1] All elevations (el) cited herein are in meters, referenced to the National Geodetic Vertical Datum (NGVD).

the model can be obtained from the University of Mississippi (e-mail address: *ncche@olemiss.edu*).

A comprehensive set of field data was collected during June 1998 to support the study. A high-resolution multibeam sweep survey was conducted to define the bendway bathymetry and resolve the individual weirs. Six gauges were employed at various boundaries to measure the water-surface elevation. Additionally, Acoustic Doppler Current Profile (ADCP) data were taken over 34 transects in Victoria Bend. This comprehensive data set was used to validate the three-dimensional model. Figure 3 shows the bathymetry and velocity transect locations in the bendway.

**MODEL DESIGN:** The first step in the modeling process was to estimate the channel roughness in Victoria Bend. The discharge through Victoria Bend was computed by integrating the velocity profile data over the bendway cross-sectional area. The energy slope was measured using the water-surface elevation gauges upstream and downstream of the bendway. The Manning roughness coefficient was determined by trial and error. A two-dimensional model (CCHE2D) was run to evaluate the average Manning coefficient. Model runs were performed over a range of Manning coefficients until the computed energy slope matched the measured slope across the bendway.

The Manning coefficient computed using the CCHE2D model was transformed to roughness height for use in the three-dimensional model CCHE3D that uses a wall function as a boundary condition. The roughness height is defined by:

$$n = \frac{d^{1/6}}{A} \tag{1}$$

where

$d$ = equivalent roughness height

$n$ = Manning coefficient

$A$ = an empirical constant with the value of 19

The three-dimensional mesh was highly resolved, with 125 transverse elements, 322 longitudinal elements, and 11 vertical elements. This resolution was necessary to adequately define the weir elevation and geometry, and to evaluate in detail the three-dimensional longitudinal and transverse flow patterns. Approximately 16 km of river channel were modeled, with the upstream and downstream model boundaries located about 8 km above and below the bendway respectively (Figure 1). The respective boundary conditions for the steady-state simulation consisted of an inflow boundary of 12,610 cu m/sec and a downstream water-surface elevation of approximately el 39.6.

**MODEL VALIDATION:** The model was validated by comparing computed velocity to measured velocity. The ADCP data set consisted of velocity components as well as the total or resultant velocity. The velocity components were defined by the Cartesian coordinate system, i.e., x component (east), y component (north), and z component (vertical). Figure 4 depicts the

location of 34 ADCP transects throughout the bendway. They are numbered 1-34, with the survey number in parentheses. At selected measurement locations (approximately 10 per transect), the measured velocity as well as measured velocity magnitude were compared to computed values as a function of depth. Over 300 comparison plots were generated to validate the model. Overall, the model was in very good agreement with the measured data for both the near and far field locations in the bendway. Additionally, velocity data were compared along the thalweg of the channel. Figure 5 shows the measurement locations as red dots along the channel.

**RESULTS:** The Victoria Bend flow field was examined in both two and three dimensions. The two-dimensional depth-averaged model simulation was conducted to evaluate the general flow characteristics throughout the bendway, whereas the three-dimensional model was used to examine the near field flow, particularly the transverse helical secondary flow, and the change in flow angle adjacent to the weirs.

**Two-Dimensional Model Results:** The depth-averaged flow field in Victoria Bend was computed to evaluate the general flow characteristics of the bendway for the 12,160-cu m/sec simulation. Figure 6 presents the Victoria Bend velocity field in terms of vectors and contours. Generally, the flow accelerates over the weirs due to constriction of flow and decelerates between weirs. The dikes on the inside of the bendway effectively route the flow towards the center of the channel. Just below the lowermost weir, the flow routed by the dikes from the inside of the bendway and the flow distributed outside of the bendway join in a narrow, deep channel with a substantial increase in velocity.

**Three-Dimensional Model Results:** To effectively evaluate the three-dimensional bendway flow, an orthogonal mesh was generated along the main channel (Figure 7). The longitudinal lines of the mesh are along the main flow direction (longitudinal) with the transverse flow lines perpendicular. The longitudinal and secondary flow velocity can therefore be obtained by projecting the velocity components (x and y) onto the longitudinal and horizontal mesh lines. The effect of the weirs on the main channel flow field can therefore be evaluated from the variation of the longitudinal and transverse velocities. The mesh has 27 sections as shown in Figure 7. For comparison purposes, model simulations were performed for Victoria Bend with and without weirs.

*Influence of bendway weirs on secondary flow.* The transverse secondary helical flow was evaluated by projecting the flow velocity components onto the orthogonal mesh. Contour and vector plots were made comparing the secondary flow with and without weirs at each of the 27 sections (Figure 7). Figure 8 shows the helical flow pattern with weirs (left side of the figure) and without weirs (right side of figure) for sections 13, 14, and 15 as depicted in Figure 7. Sections 14 and 15 are adjacent to the fourth weir (as referenced from the top of the bend). The flow field indicates that the presence of the weir disrupts and reduces the magnitude of the secondary flow along the length of the weir. Around the weirs, the secondary flow is separated into two parts: the secondary flow from the inside of the bend and secondary flow that forms due to the weirs. Between the weirs, the normal secondary flow pattern tends to reform.

*Influence of bendway weirs on flow direction near the free surface.* It has been observed in physical model simulations of submerged weir fields that the flow over the weirs realigns in a

direction perpendicular to the downstream weir face. This change in flow angle results in a realignment of the flow away from the outside of the bend. The magnitude and duration of this flow angle change is an indicator of weir effectiveness in improving navigation conditions and is therefore important for optimizing weir design. The direction of the near-surface flow is defined by the angle

$$\theta = \arctan\left(U_{transversal} / U_{longitudinal}\right) \tag{2}$$

with $U$ the flow velocity.

*Flow angle simulations.* Three simulations were conducted to evaluate flow angle across the weirs in the main channel of the bendway: (a) the change in flow angle for the bendway with and without weirs, (b) the change in flow angle at different depths for the bendway with and without weirs, and (c) the change in flow angle for the bendway with weirs with a smooth bed and with the existing bed (scour holes).

*Case Simulation 1 – flow angle with and without weirs.* The change in flow angle is presented in Figures 9 and 10 for flow with and without weirs in the channel. An increasing angle indicates flow increasing towards the outside of the bendway. A decreasing angle indicates flow towards the inside of the bend. Figures 9 and 10 show that the submerged weirs change the flow angle towards the inside of the bend for surface flow. The difference between the two conditions is shown in Figure 11 ($\theta_{\text{with weirs}}$ - $\theta_{\text{without weirs}}$). Only contours that show an improved condition are included. This clearly shows that the flow angle has improved adjacent to the weir locations.

*Case simulation 2 – flow angle at varying depths.* Figures 12 and 13 present the flow angle at approximately 5-6 and 10-11 m below the surface. These results indicate that the change in flow angle is relatively constant with depth.

*Case simulation 3 - flow angle with bed change.* To evaluate the effect of bed change on weir performance, the existing bathymetry containing scour holes below each weir was changed to reflect a smooth bed. The results of this simulation are presented in Figure 14. When compared to the weir field simulation with scour holes below the weirs (Figure 9), it is apparent that bed changes (scour) that occurred since the weirs were constructed had a minimal effect on flow characteristics in the bendway and the performance of the weirs.

**CONCLUSIONS:** Conclusions based on the modeling results are as follows:

*a.* The two-dimensional depth-averaged simulation revealed general flow characteristics through the bendway. However, the two-dimensional simulation did not reveal a significant redistribution or realignment of the flow from the outside of the bend to the inside.

*b.* The three-dimensional simulation captured the changes in transverse helical flow magnitude and direction, which are important variables for future design considerations.

*c.* Model results show that the presence of submerged weirs disrupts the transverse helical flows in the immediate vicinity of the weirs.

*d.* Model results indicate that the flow angle or flow realignment in the bendway is improved by the submerged weirs, and that flow realignment is relatively constant with depth.

*e.* Model results indicate that changes in the bed condition (scour holes and depositional areas) that occur after the weirs were constructed have a minimal effect on the ability of weirs to improve flow alignment / distribution in the bendway.

**FUTURE INVESTIGATIONS:** This modeling effort was an important first step in quantifying how bendway weirs affect the flow distribution in bendways. Small-scale physical model tests and prototype installations have revealed substantial qualitative data on bendway weir field performance, yet no proven design criteria exists that relates bendway hydrodynamics to weir field design variables such as weir length, weir width, weir height, bend radii, depth of water above the weir, and weir angle.

The results of this study indicate that a three-dimensional numerical model is capable of evaluating near field three-dimensional bendway flow patterns such as secondary helical flows. The ability of the weir field to disrupt the secondary flows and, thus, realign the flow away from the outer bank is a primary project design goal, therefore the three-dimensional model may prove to be a valuable design tool. Presently, a bendway weir physical model is being modeled with the three-dimensional model. A parametric evaluation is being performed to evaluate the impact of various design variables on reducing the magnitude of the helical flows and thus improving navigation. The end product from these studies is first-generation design guidance based on the hydrodynamics of weir fields. Additional work is planned for analyzing the impacts of sediment transport characteristics (scour and filling) on the effectiveness of weir fields. Ultimately, comprehensive design guidance will be developed that will detail the most effective weir field design based on existing prototype bendway hydrodynamics and anticipated geomorphic changes after bendway installation.

**ADDITIONAL INFORMATION:** Questions about this CHETN can be addressed to Stephen H. Scott (601-634-2371), fax (601-634-4158), e-mail *scotts@wes.army.mil*. This CHETN should be referenced as follows:

Scott, S. H., Jia, Y., Wang, S. S. Y., and Xu, Y. (2001). "Analysis of near field hydrodynamics of submerged weirs," Coastal and Hydraulics Engineering Technical Note CHETN-VII-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
*http://chl.wes.army.mil/library/publications/chetn/*

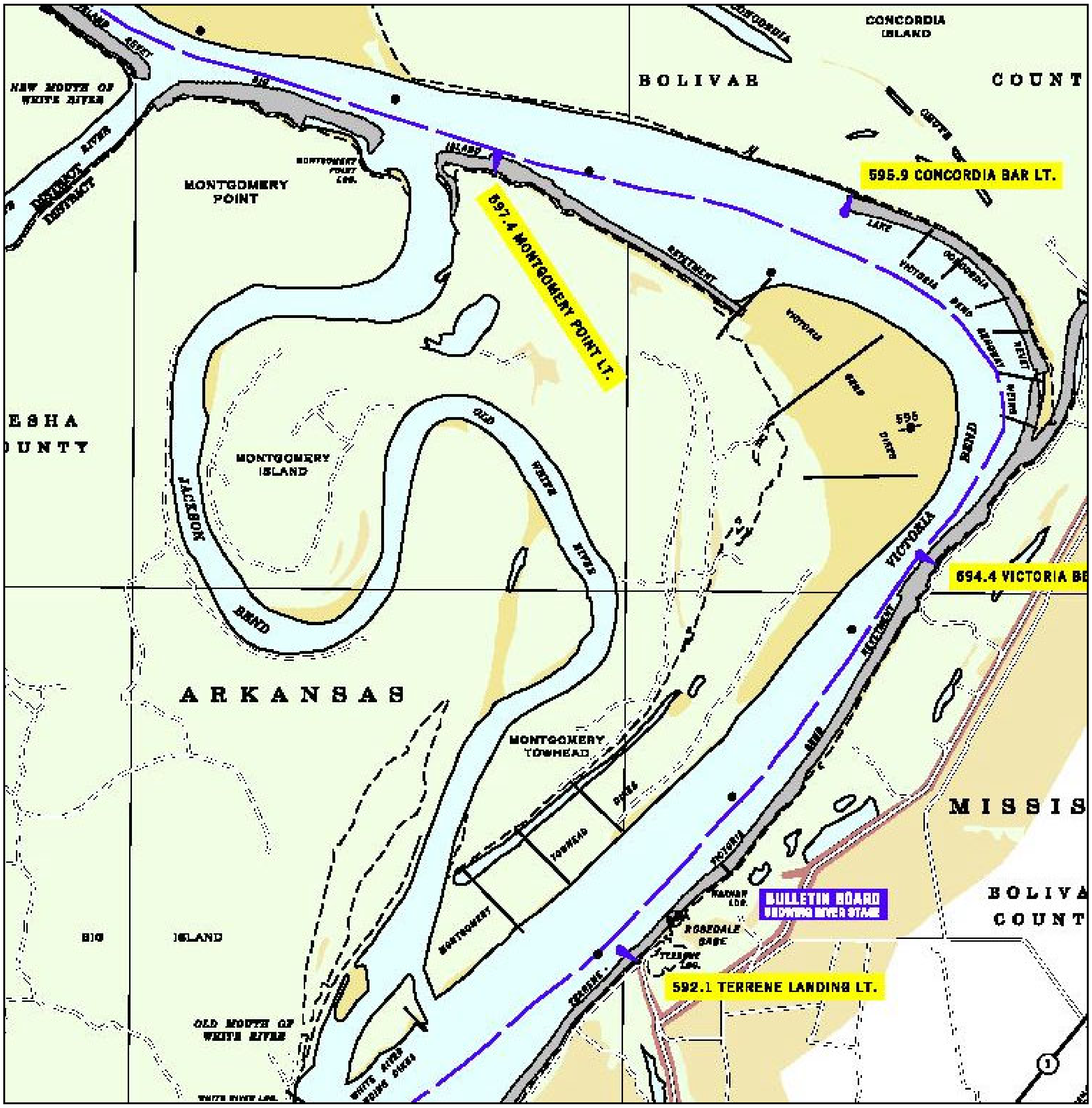


Figure 1. Victoria Bend in the Mississippi River

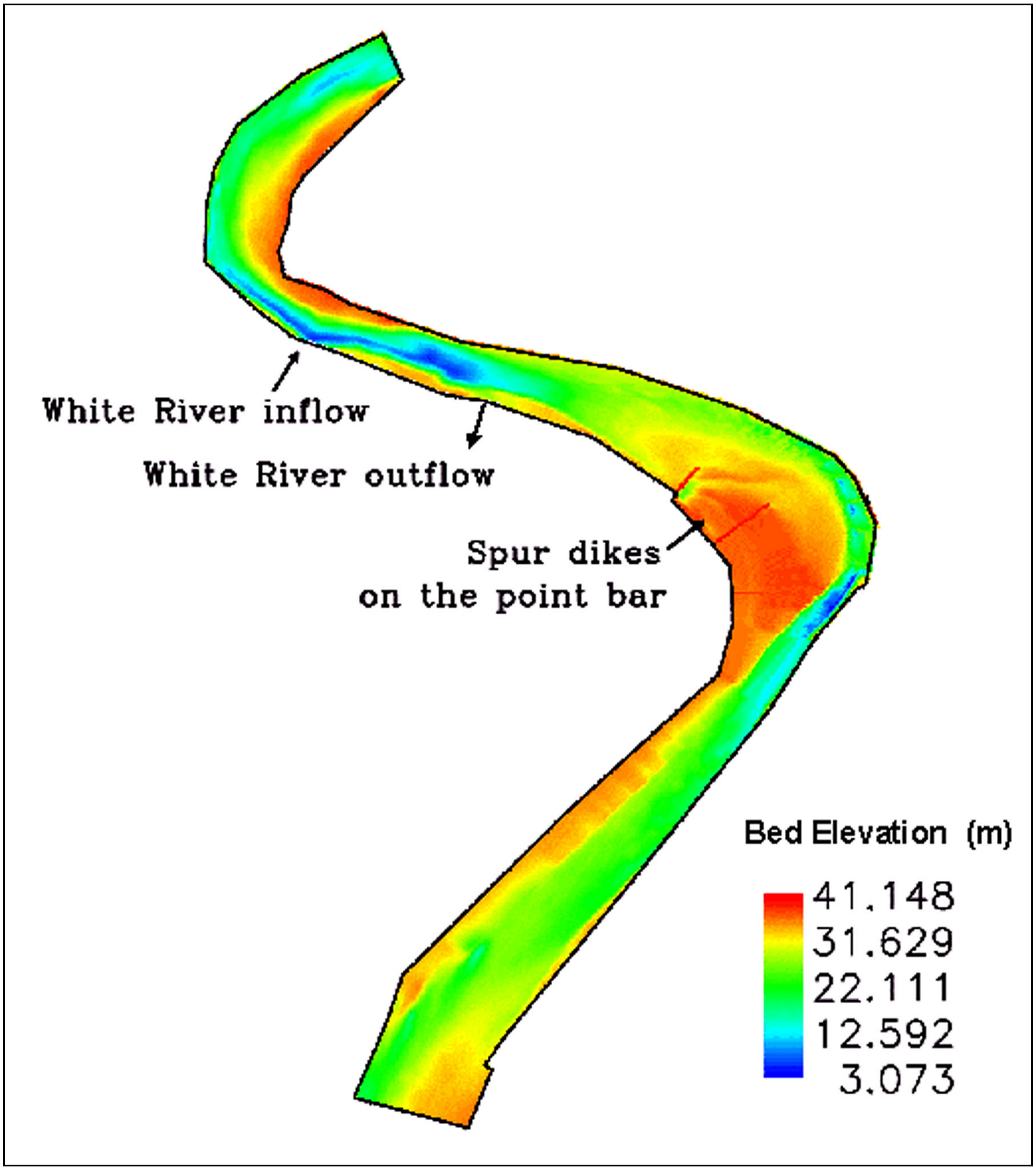


Figure 2. Bathymetry in Victoria Bend

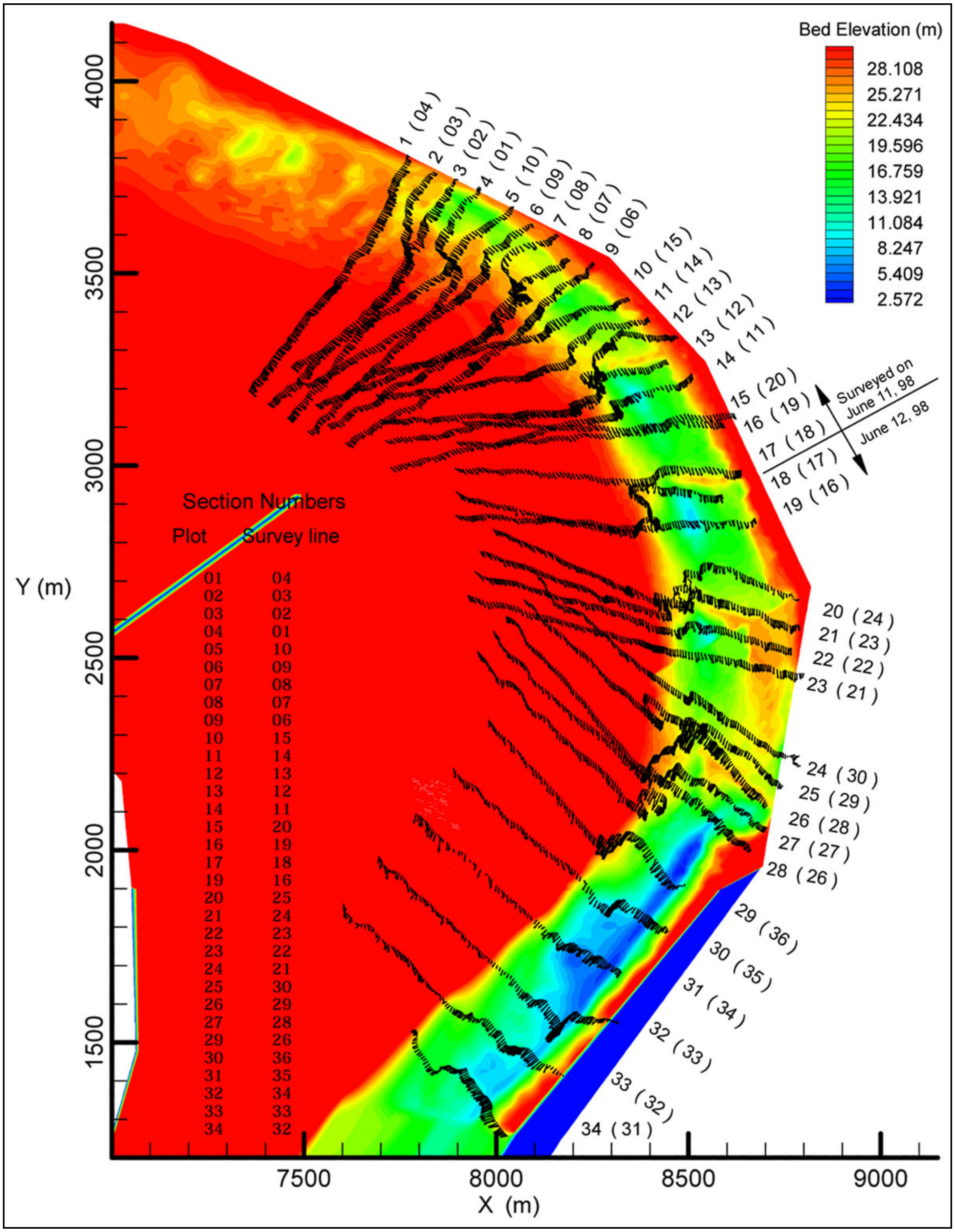


Figure 3. Velocity transect locations along Victoria Bend

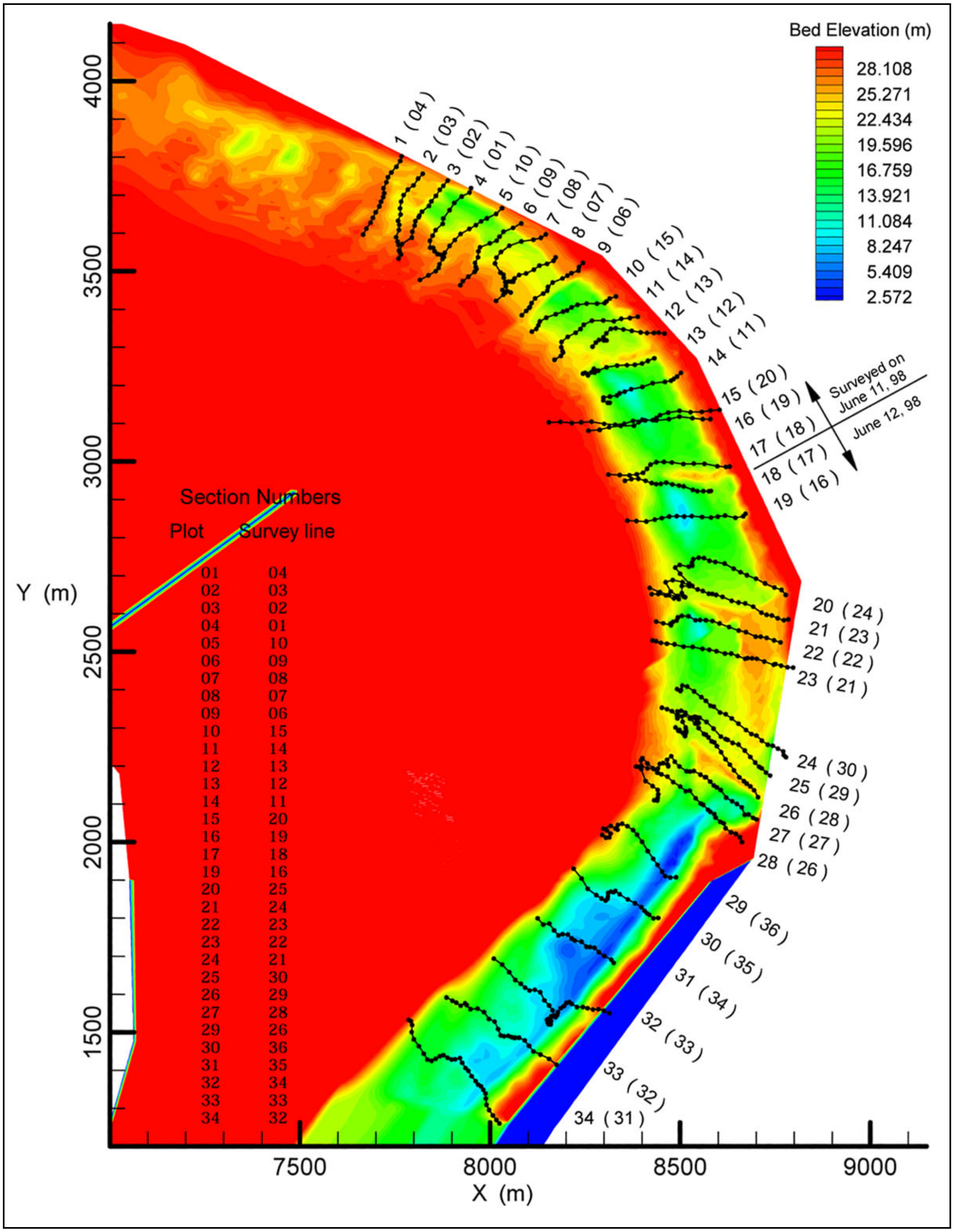


Figure 4. Model validation points along velocity transects

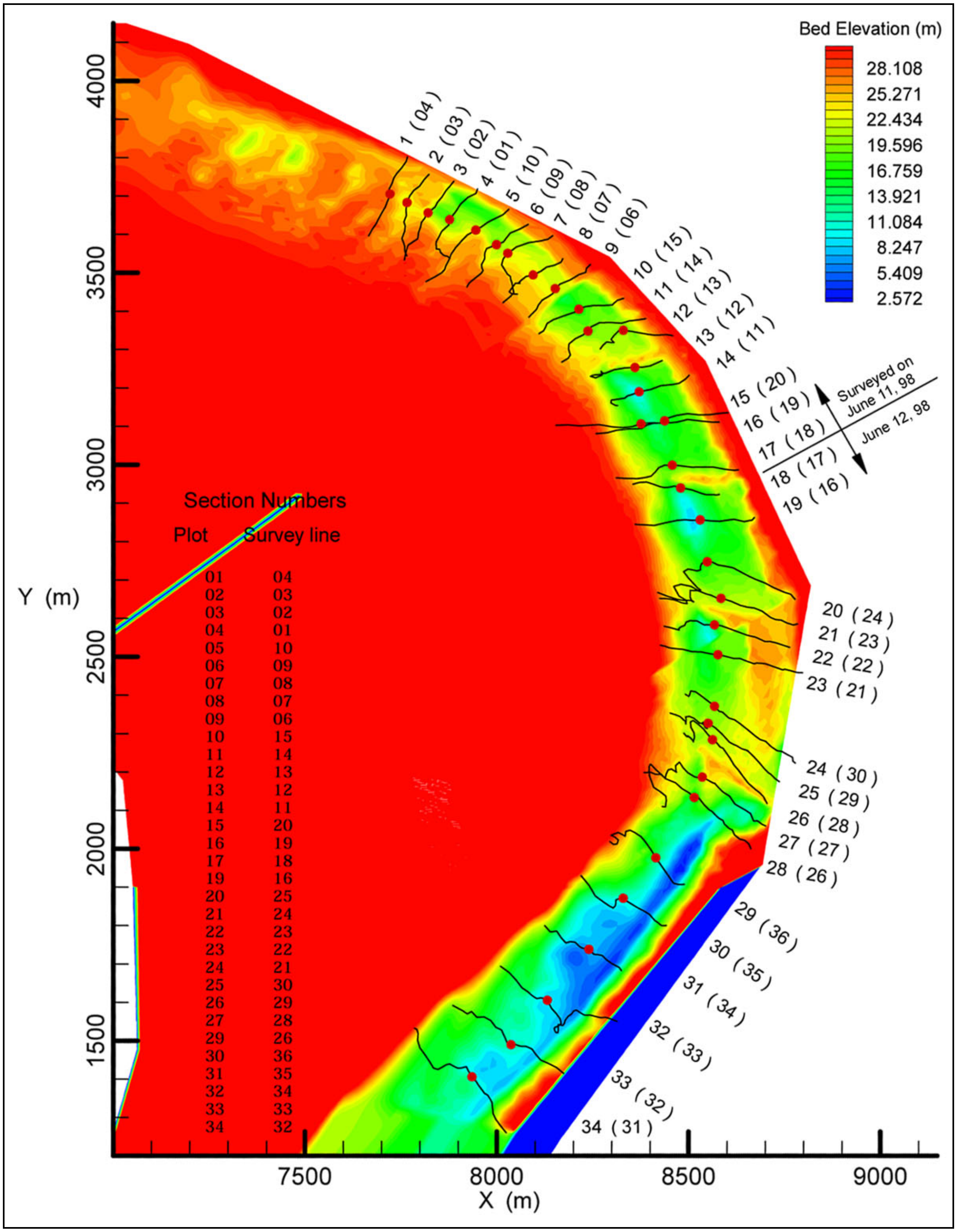


Figure 5. Velocity validation points along the channel thalweg

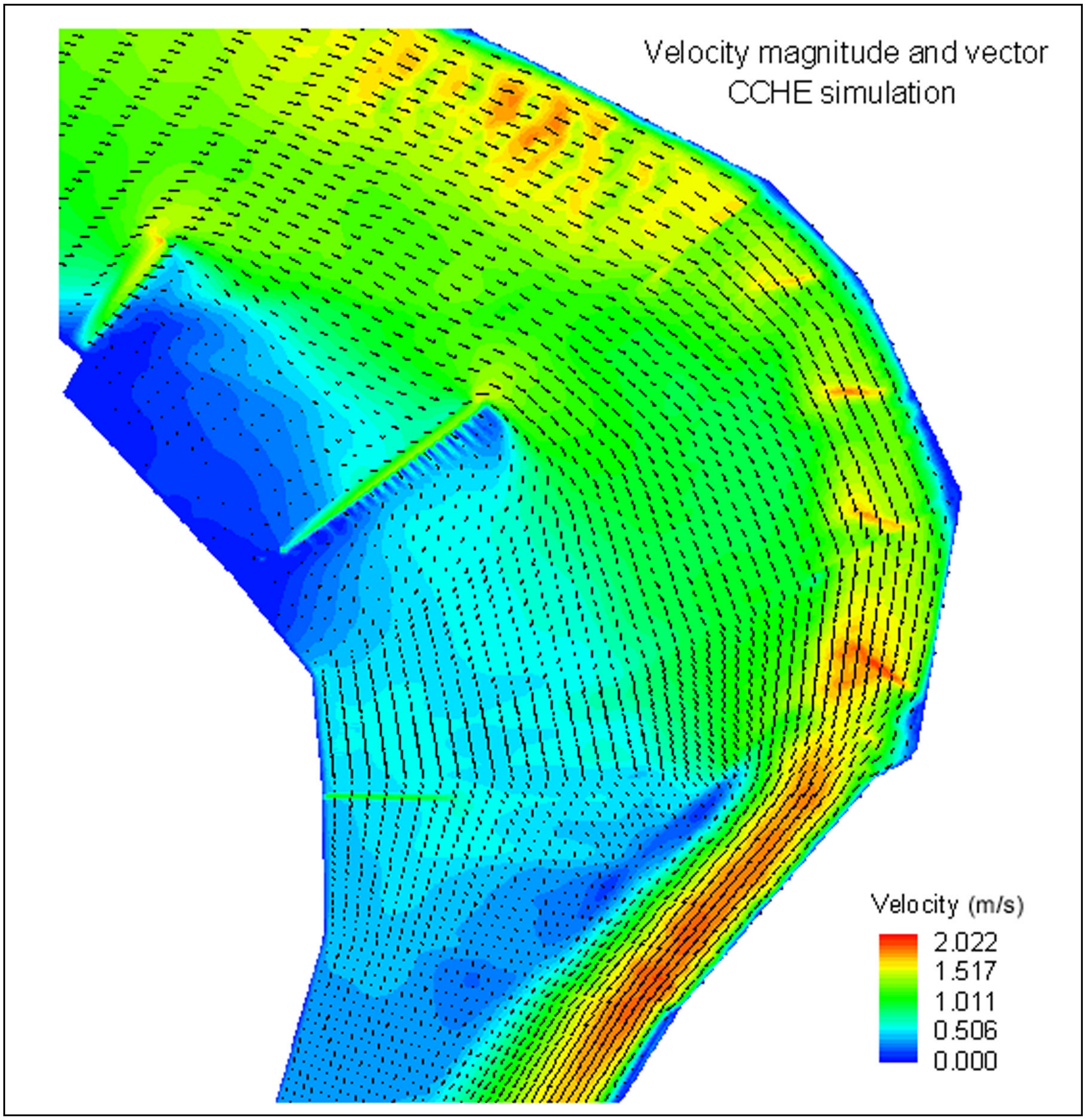


Figure 6. Two-dimensional model simulation of flow through Victoria Bend

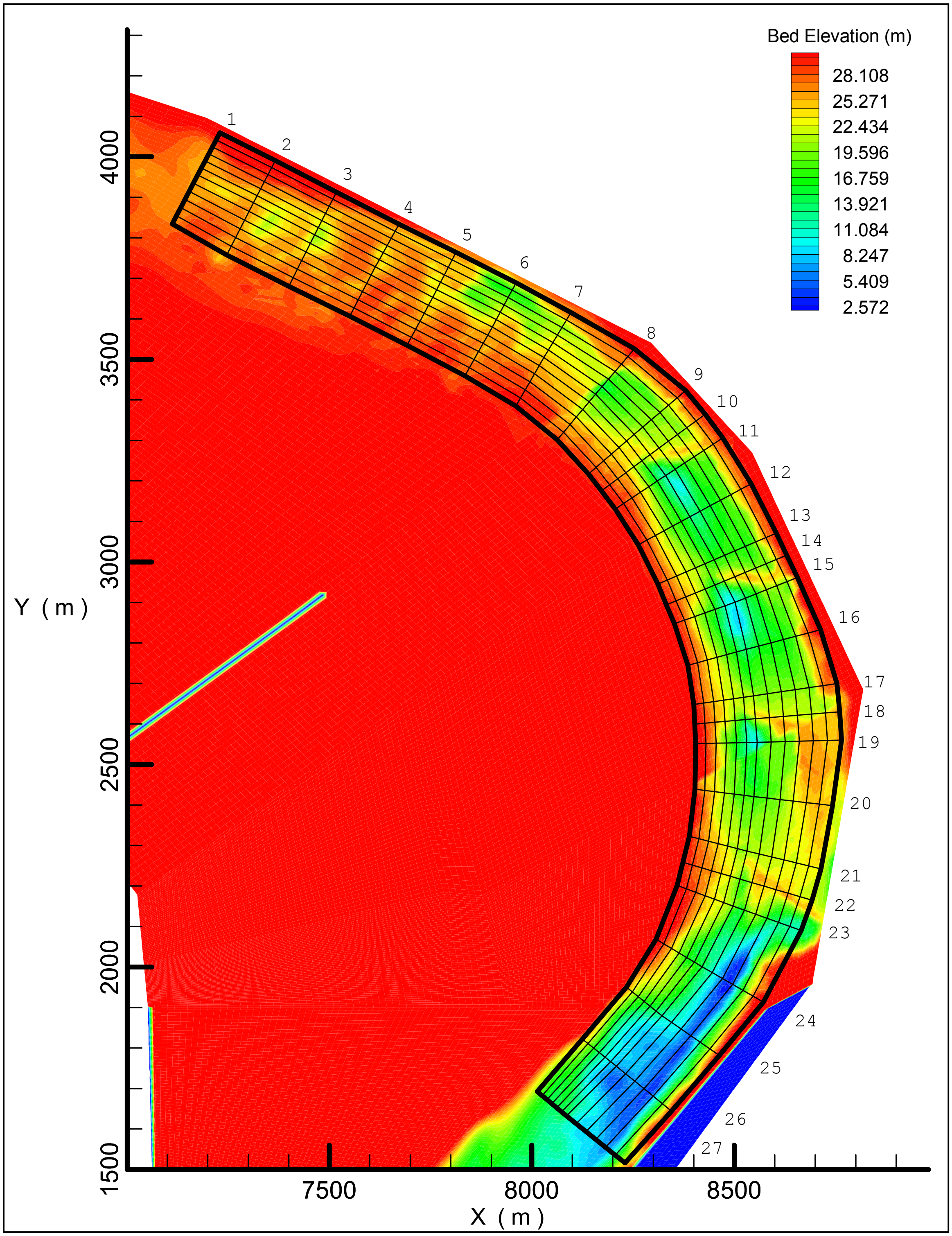


Figure 7. Orthogonal mesh for referencing velocity components

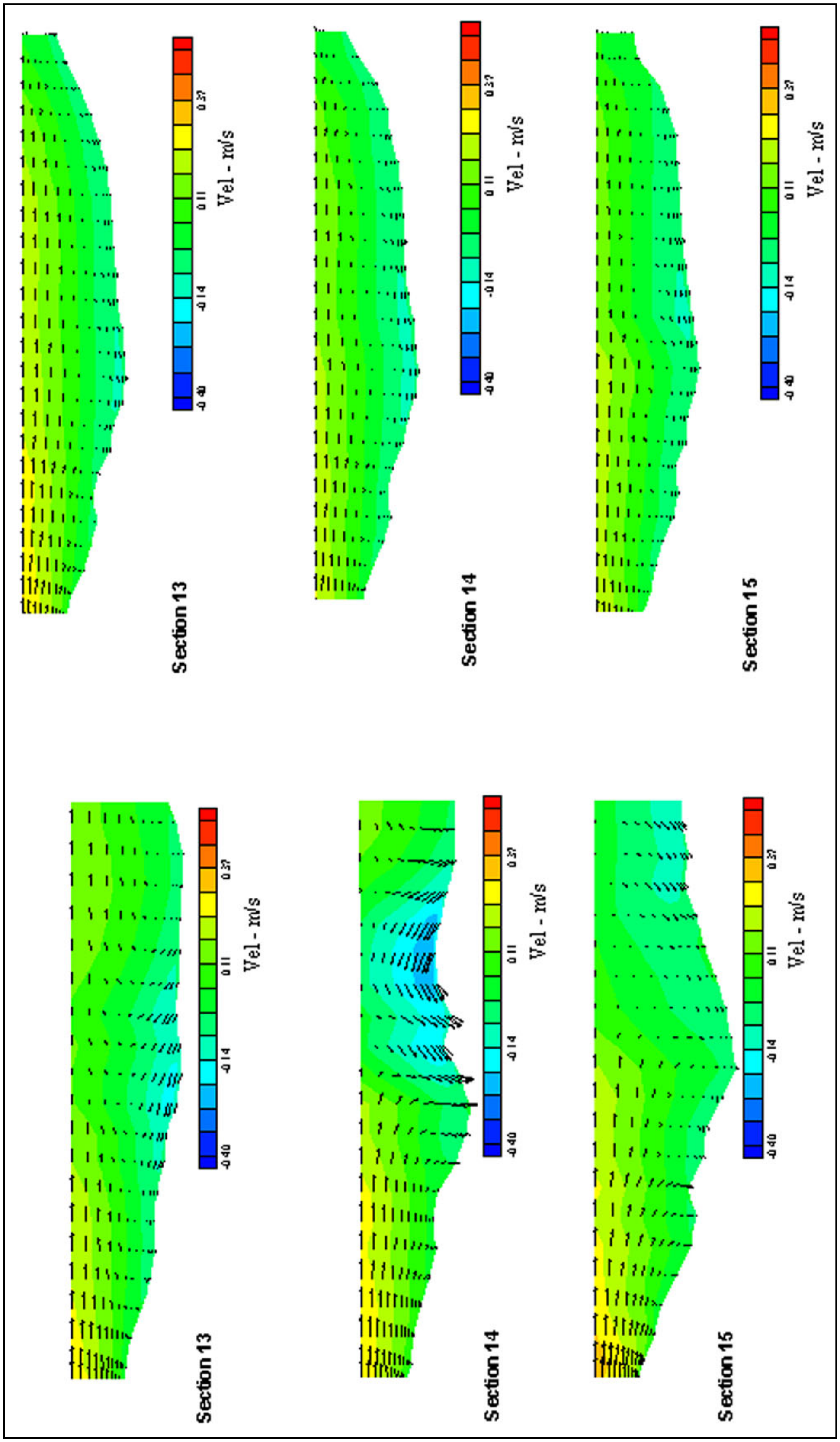


Figure 8. Transverse secondary flow with weirs (left side) and without weirs (right side)

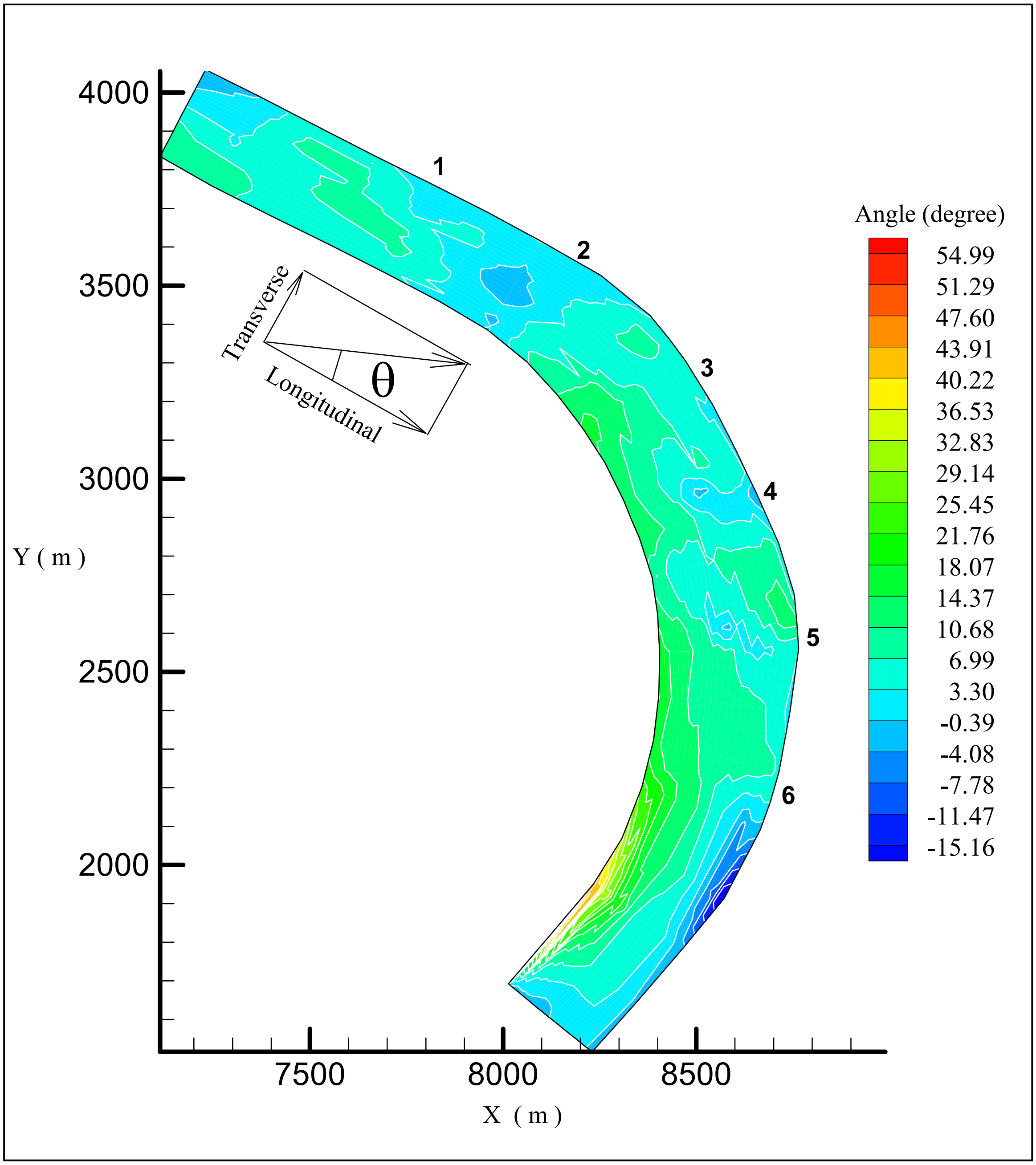


Figure 9. Flow angle for Victoria Bend

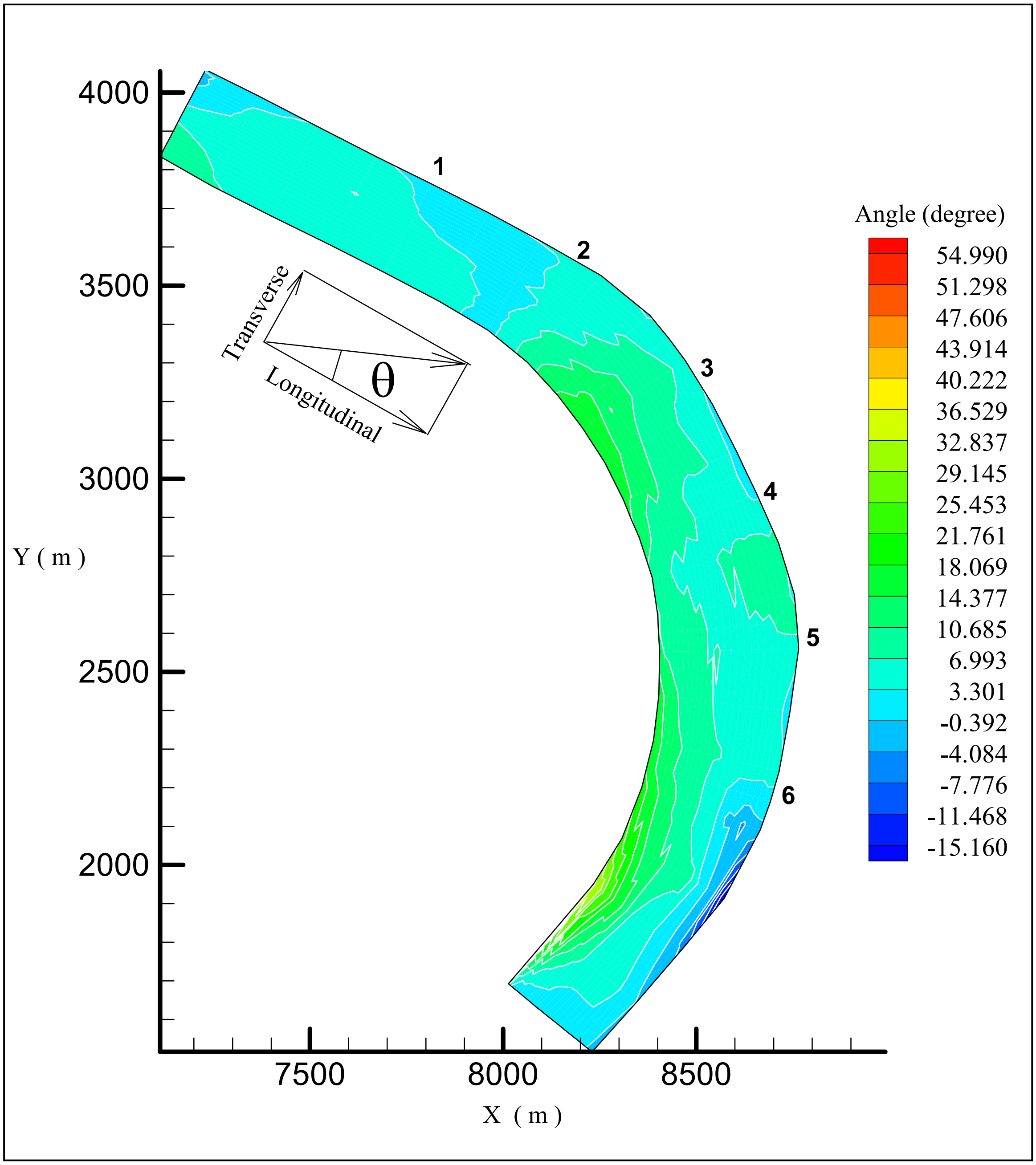


Figure 10. Flow angle in Victoria Bend without submerged weirs

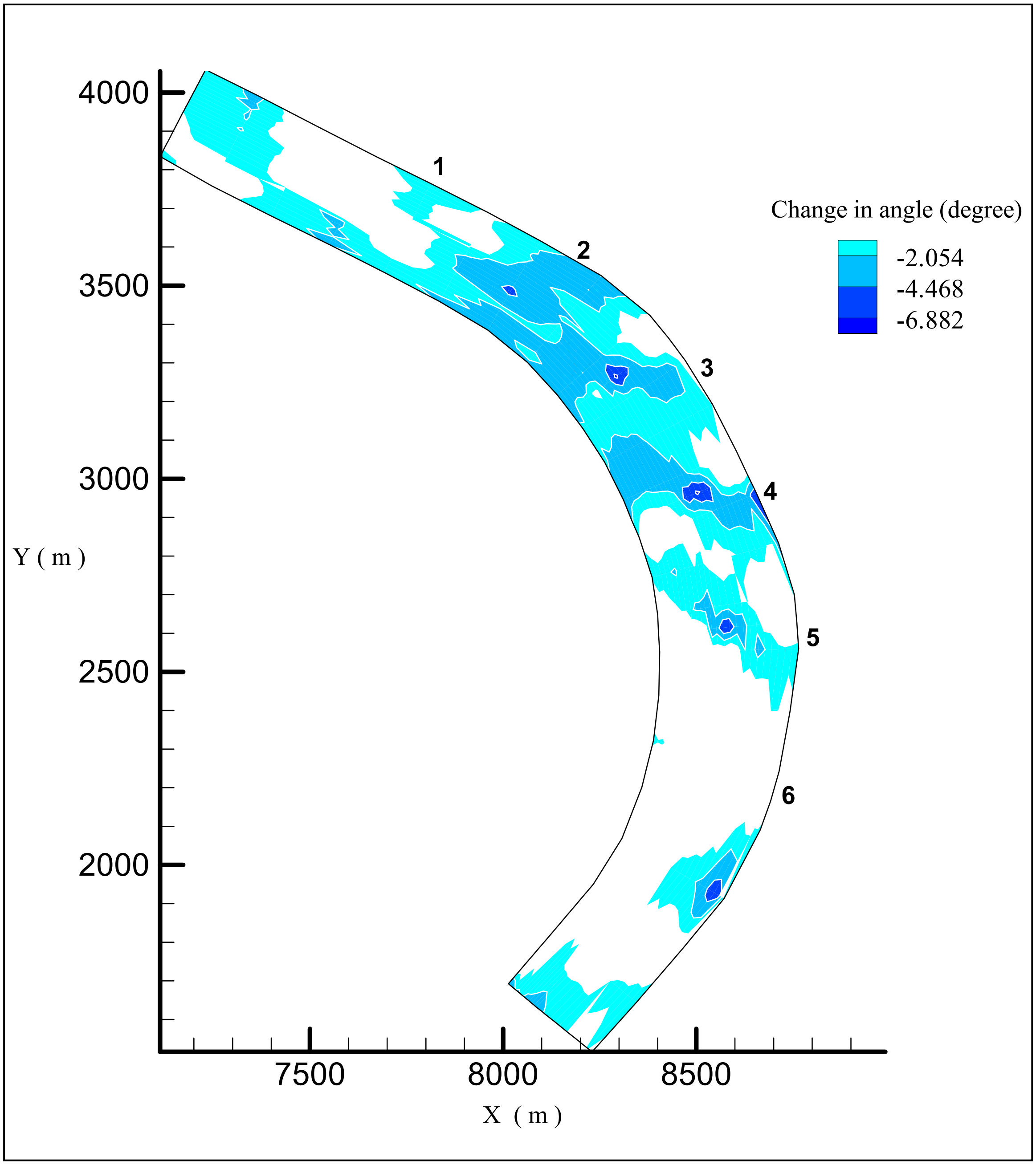


Figure 11. Difference in flow angle between flow conditions with weirs and without weirs (only improved conditions contoured)

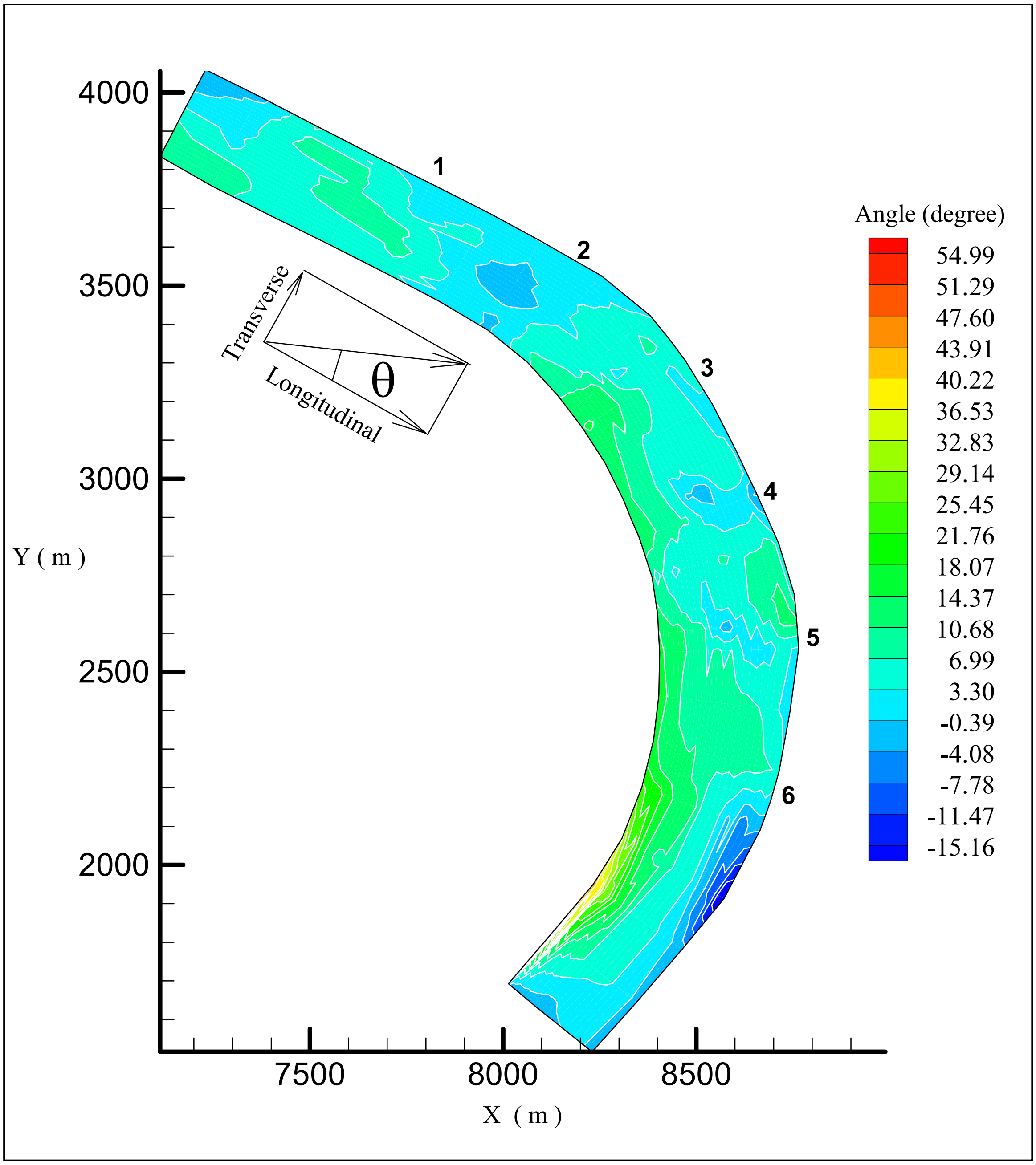


Figure 12. Flow angle at approximately 5-6 m depth

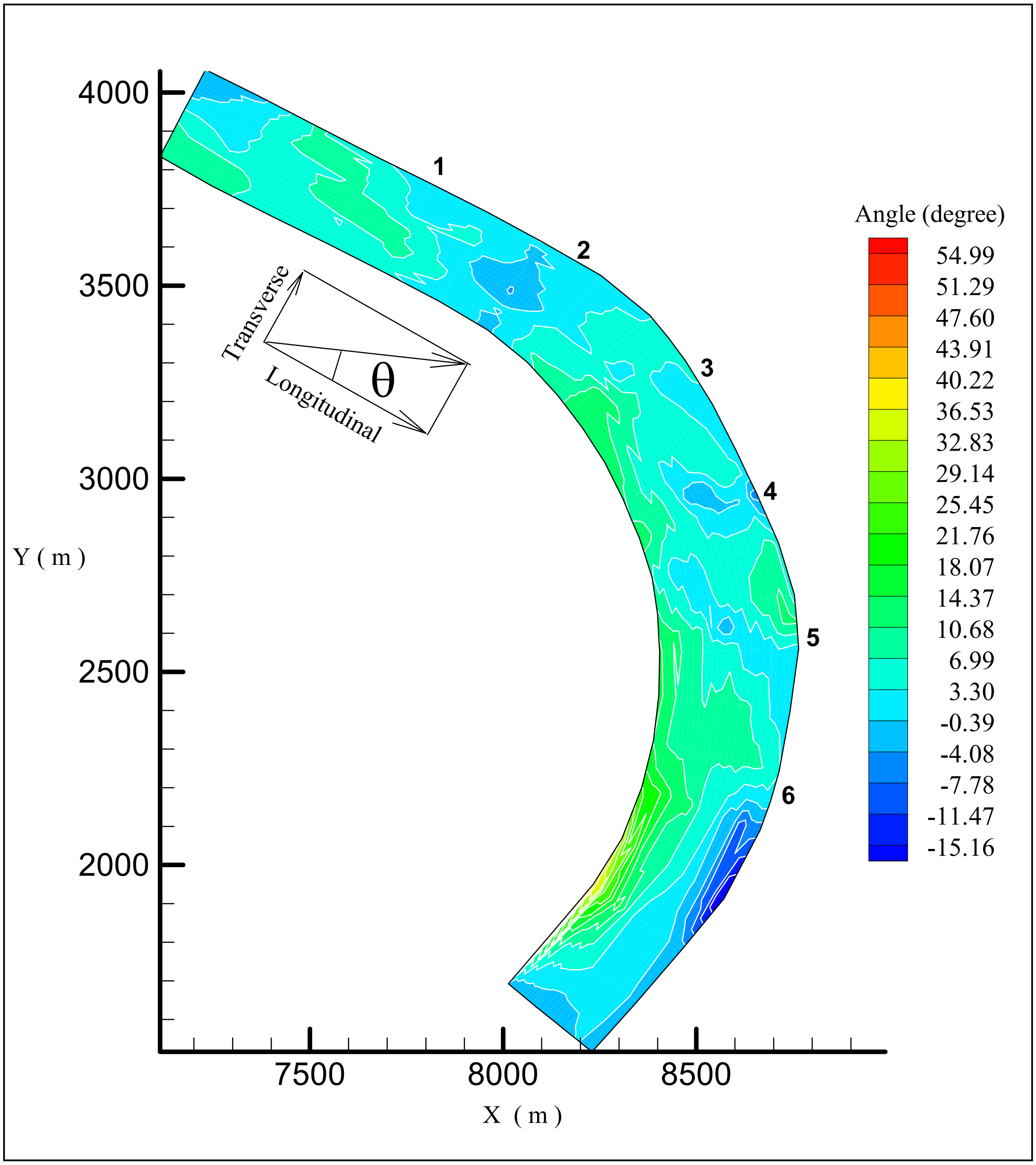


Figure 13. Flow angle for approximately 10-11-m depth

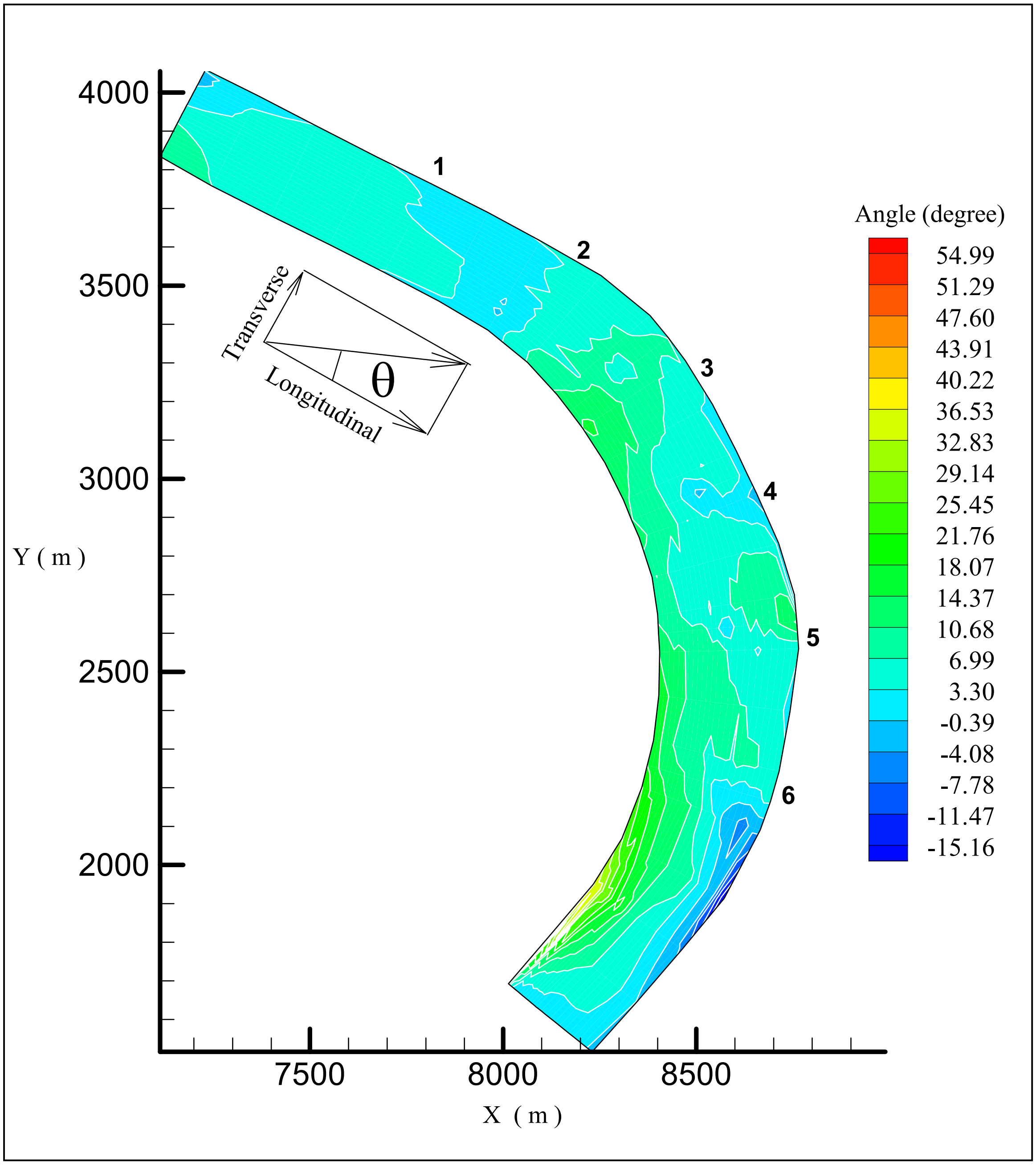


Figure 14. Flow angle in Victoria Bend without scour holes